"Novel" simulation approaches for plasma accelerators and fast ignition

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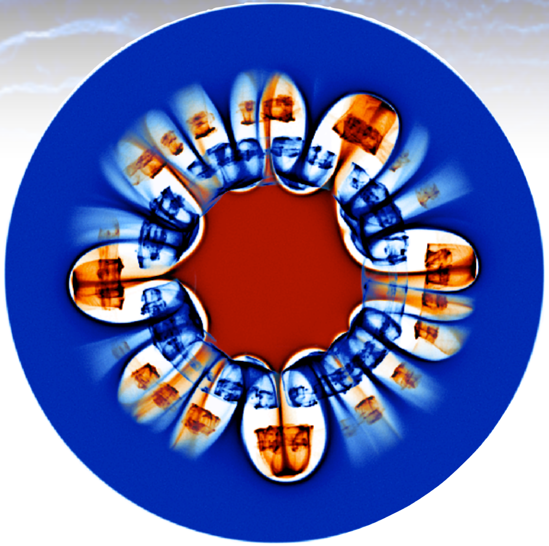

Accelerates ERC-2010-AdG 267841

Acknowledgments

- F. Fiúza, M. Vranic, J. Martins, J. Vieira, T. Grismayer, R. A. Fonseca
- Work in collaboration with:
  - W. B. Mori (UCLA), M. Marklund (Umea/Chalmers)
- Simulation results obtained at **epp and IST Clusters (IST), Hoffman (UCLA), Franklin (NERSC), Jaguar (ORNL), Intrepid (Argonne), and Jugene (FZ Jülich)**

erc

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OSIRIS 2.0

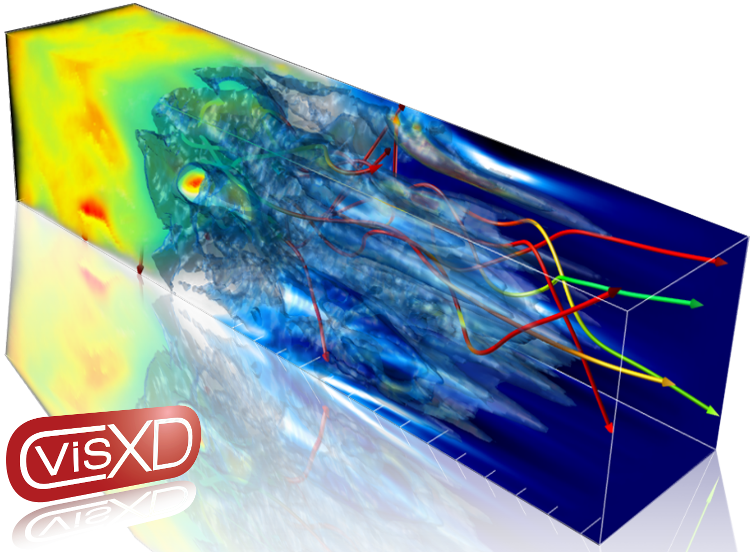
osiris
v2.0

INSTITUTO SUPERIOR TÉCNICO

UCLA

OSIRIS framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST



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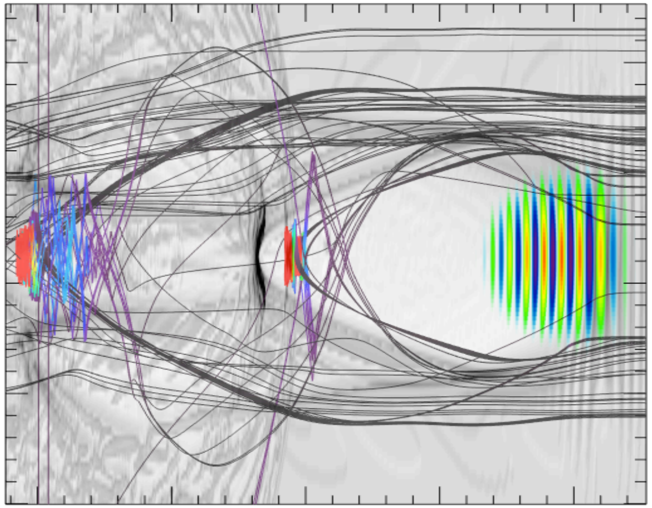
http://exodus.physics.ucla.edu/



State-of-the-art

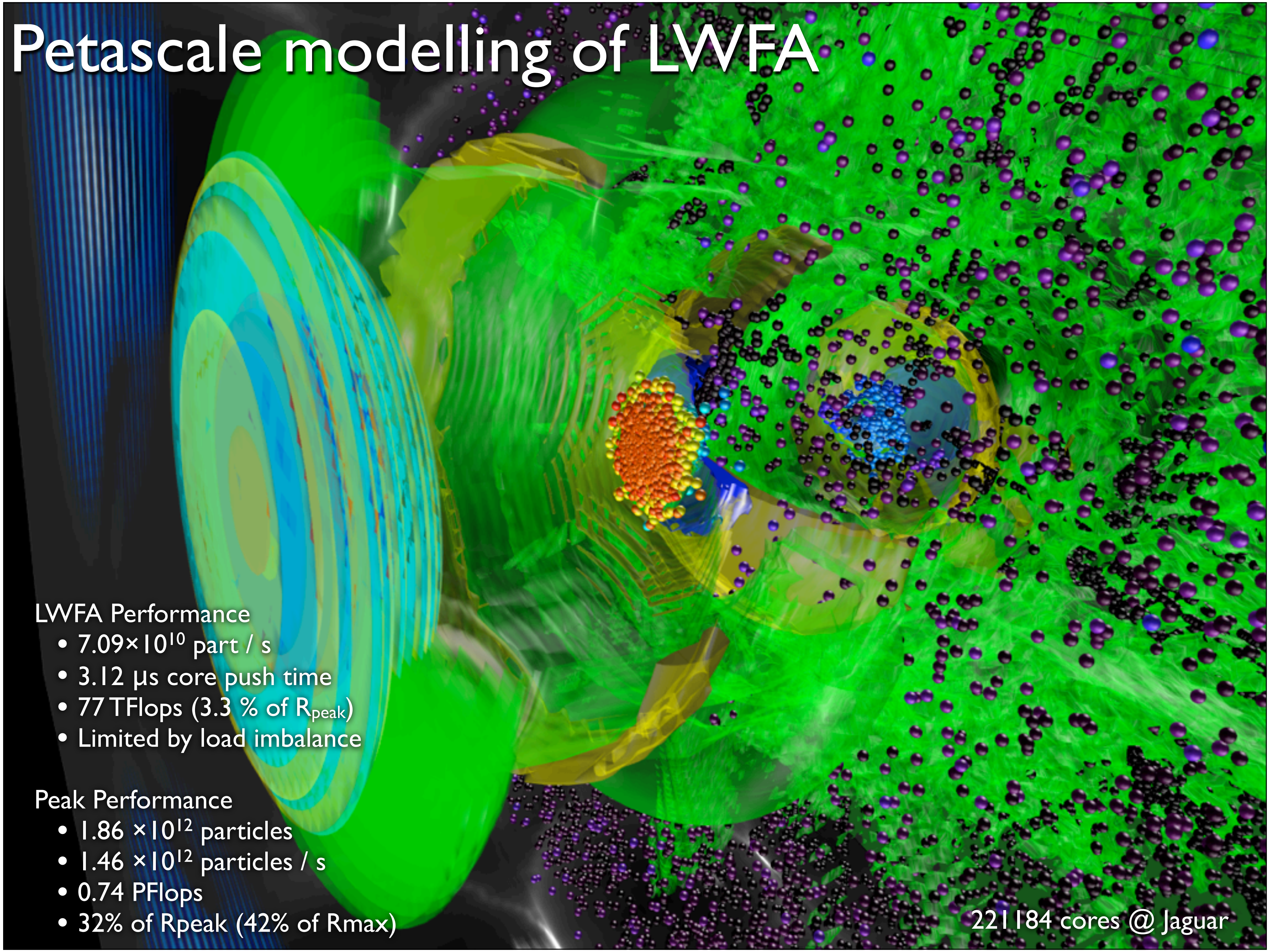
Particles: 10^{12}
Cells: 5000^3

RAM: GB - 100 TB
Time: hours - months
Data: MB - 10s TB

Broad applications

Plasma physics, astrophysics, accelerator physics, ...

Petascale modelling of LWFA



LWFA Performance

- 7.09×10^{10} part / s
- 3.12 μs core push time
- 77 TFlops (3.3 % of R_{peak})
- Limited by load imbalance

Peak Performance

- 1.86×10^{12} particles
- 1.46×10^{12} particles / s
- 0.74 PFlops
- 32% of Rpeak (42% of Rmax)

221184 cores @ Jaguar

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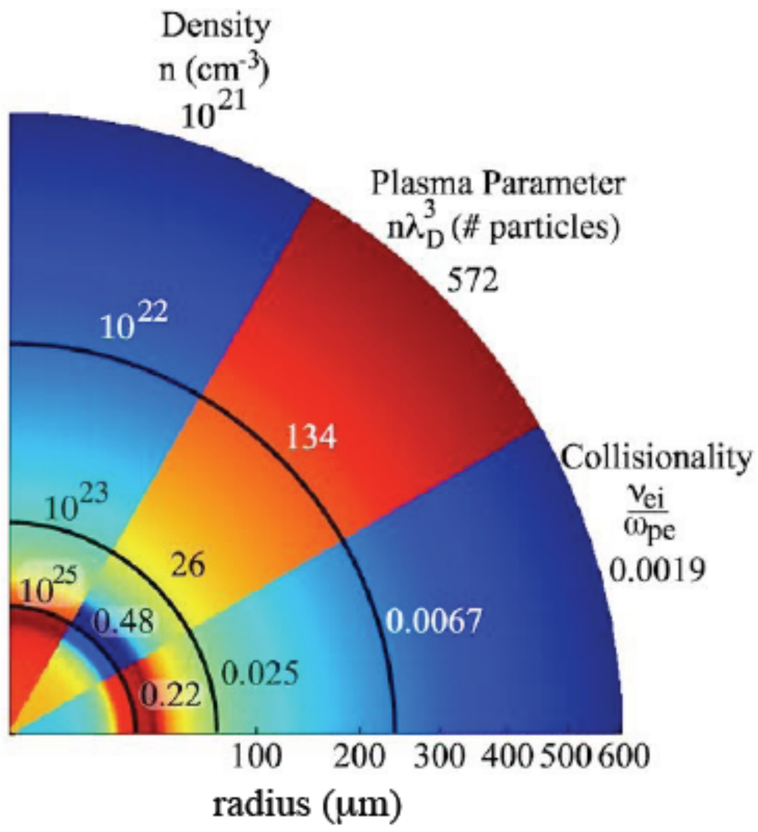
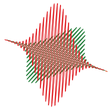
Modeling is extremely demanding due to different scales involved

Typical HED compressed target





Laser duration = 10 ps - 10 ns

Computational requirements for PIC

Physical size

Box size: 1 mm
Cell size: 5 Å
Duration: 10 ps
Time step: 1 as (10^{-18} s)

Numerical size

cells/dim: 2×10^6
particles/cell: 100 (1D); 10 (2D); 1 (3D)
time steps: 10^6

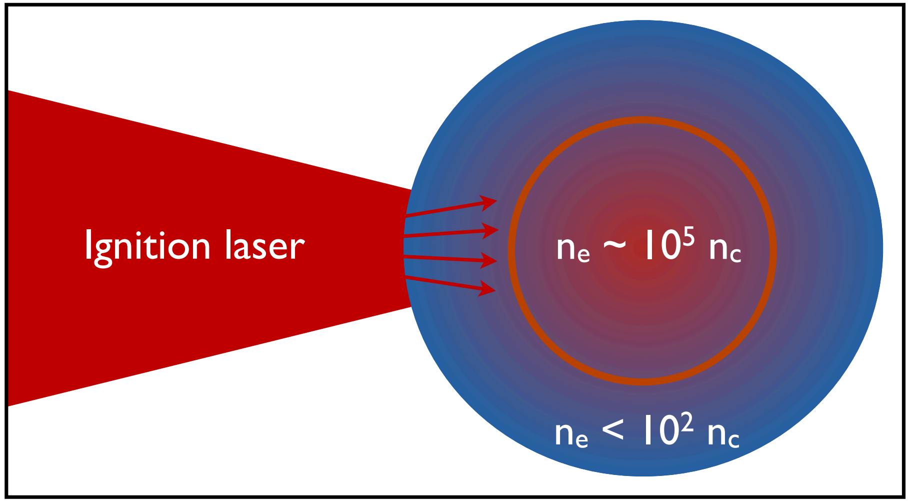
Particle push time: 1 ms

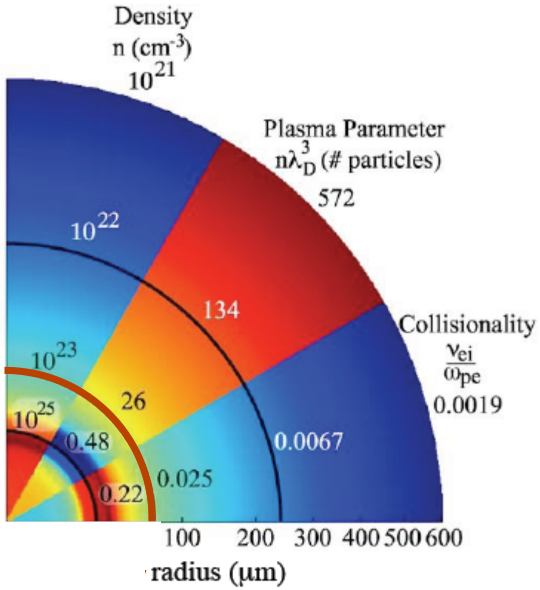
Computational time

1D - 2×10^3 CPU days
2D - 5×10^8 CPU days ~ 10^6 CPU years
3D - 2×10^{11} CPU days ~ 7×10^8 CPU years

F. Fiúza *et al*

New hybrid-PIC algorithm for HEDP modeling*





Full-PIC code

- Full Maxwell's equations
- Kinetic species
- $n_0 < 10^{23}$ cm^{-3}
- $\omega_p \Delta t < O(1)$
- $\Delta x \omega_p / c < O(1)$
- $c\Delta t/\Delta x < 1$

If resistivity (Ohm's law) matches collisional model transition is natural and self-consistent

Hybrid-PIC code

- Maxwell's equations + Ohm's law (inertialess)
- Kinetic species
- $n_0 > 10^{23}$ cm^{-3}
- $\nu_{ei} \Delta t < O(1)$
- $c\Delta t/\Delta x < 1$

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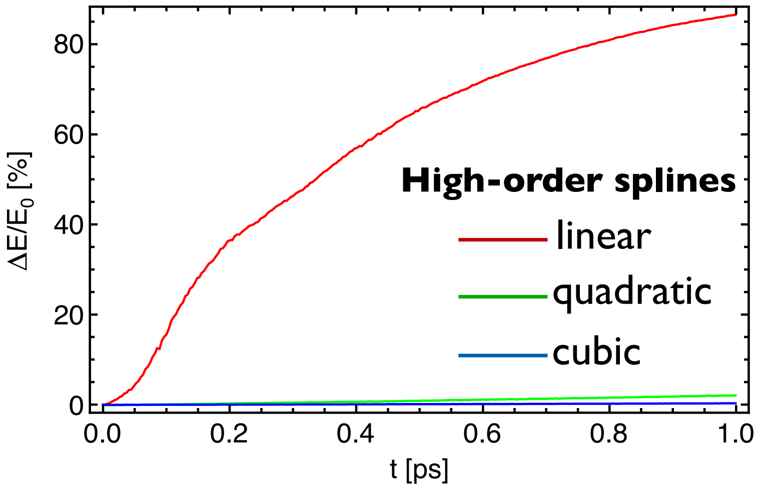
* B. Cohen, A. Kemp, L. Divol, JCP 229, 4591 (2010)

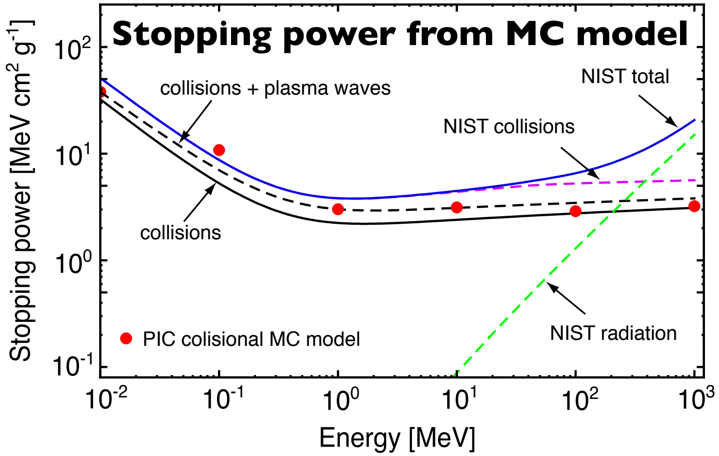
Accurate hybrid-PIC transition requires careful numerics

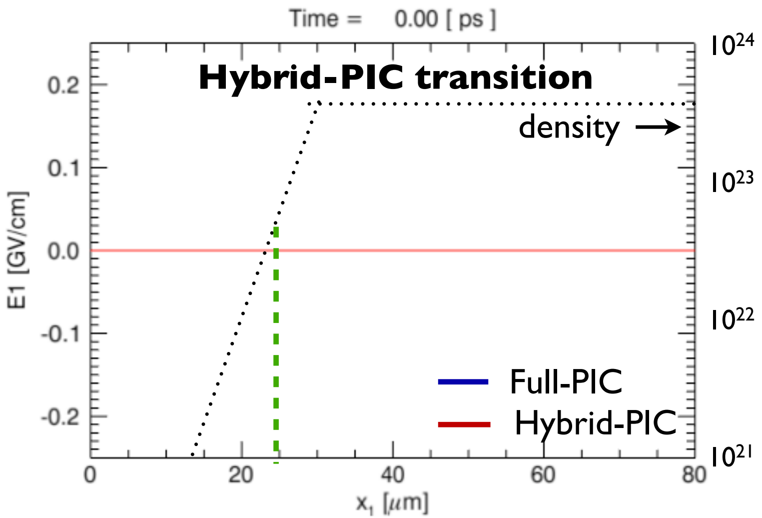
Advanced numerical techniques

- High-order splines
- MC binary Coulomb collisions
- Advanced smoothing
- PML boundary conditions



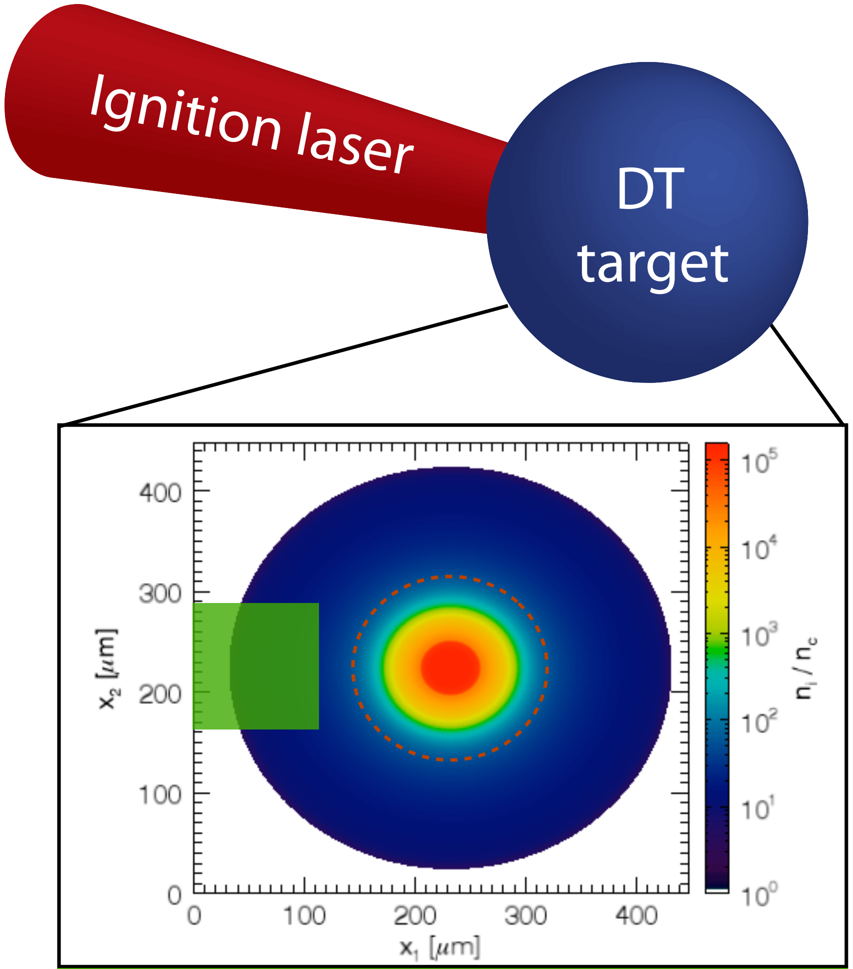
Stable and accurate transition





F. Fiuza *et al.* PPCF 53, 074004 (2011)

First full-scale FI modeling with realistic densities



Previous largest PIC simulations used a 5 kJ 2 ps laser and a 100 μm 100 n_c plasma

Physical Parameters

Laser

- λ_0 = 1 μm
- $I_0 = 2\times10^{20}$ Wcm^{-2} (100 kJ)
- W_0 = 30 μm
- **τ_0 = 15 ps**

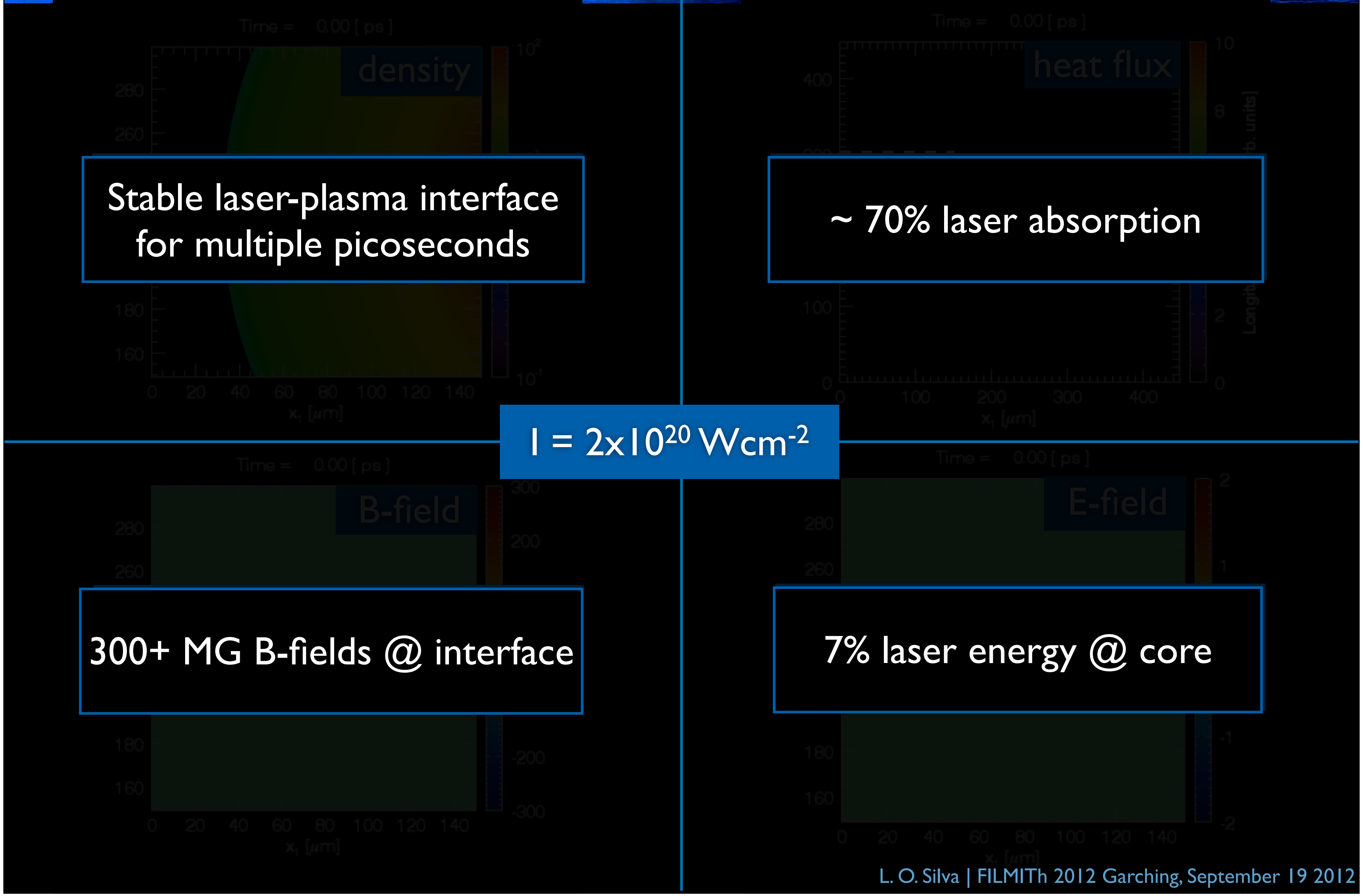
Plasma

- **L = 450 x 450 μm^2**
- **n_{e0} = 1 n_c - 2×10^5 n_c**
- m_i/m_e = 3672

Numerical Parameters

- 42 cells/μm
- hybrid/full-PIC transition = 100 n_c
- Particles per cell = 64
- # time steps = 10^5
- cubic interpolation

First full-scale FI modeling with realistic densities



Stable laser-plasma interface
for multiple picoseconds

~ 70% laser absorption

I = 2x10^{20} Wcm^{-2}

300+ MG B-fields @ interface

7% laser energy @ core

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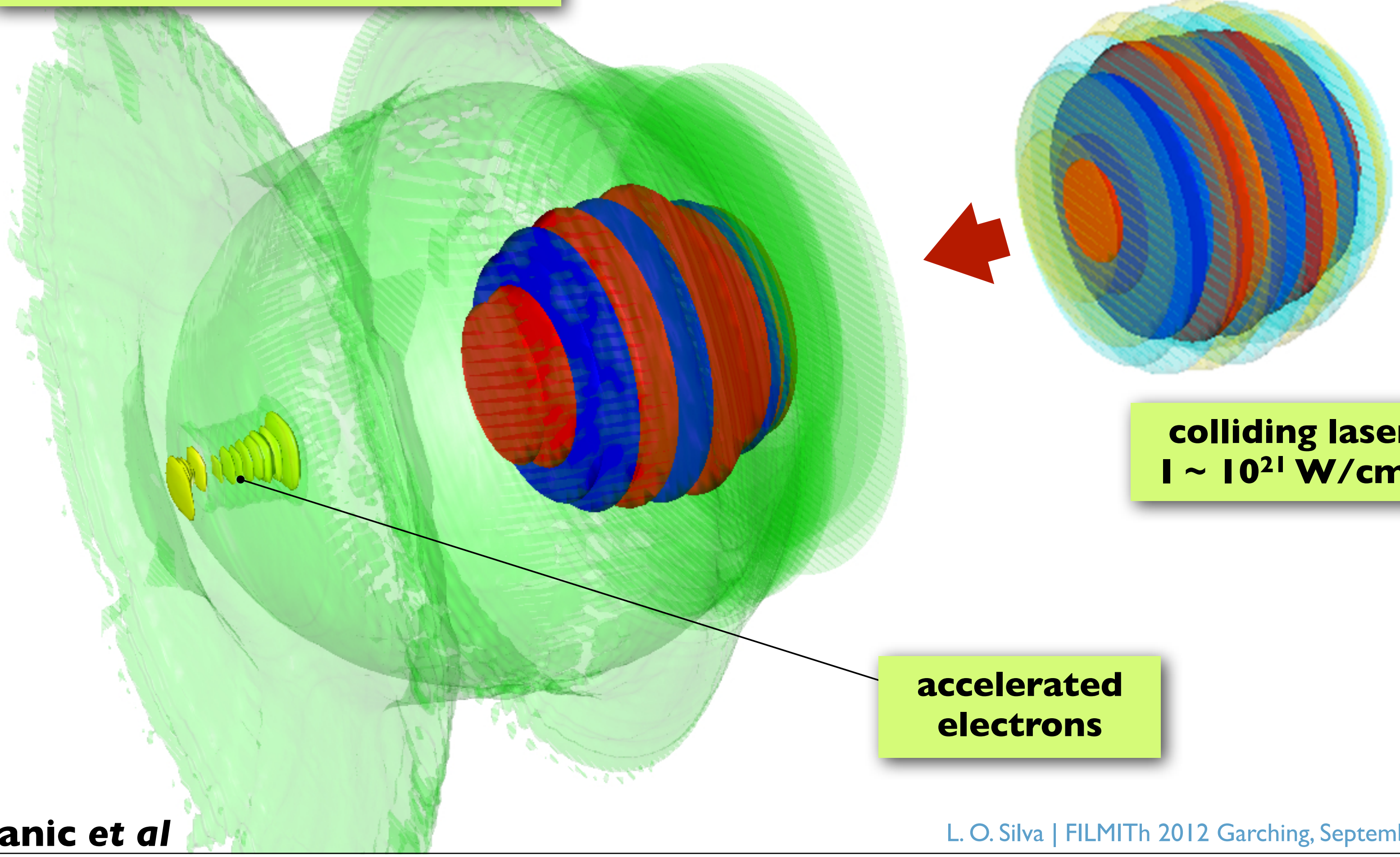
All-optical radiation reaction configuration

Identifying radiation reaction signatures in the electron beam spectrum (Astra Gemini)



laser wakefield accelerator in bubble regime

colliding laser
I ~ 10^{21} W/cm^2

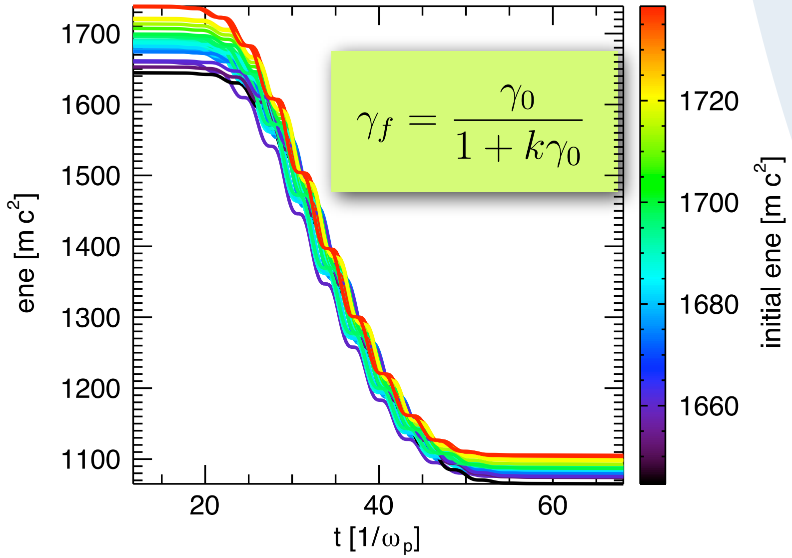
accelerated electrons

M. Vranic *et al*

Radiation reaction slows down significantly the electrons

Energy loss depends only on laser parameters and initial energy

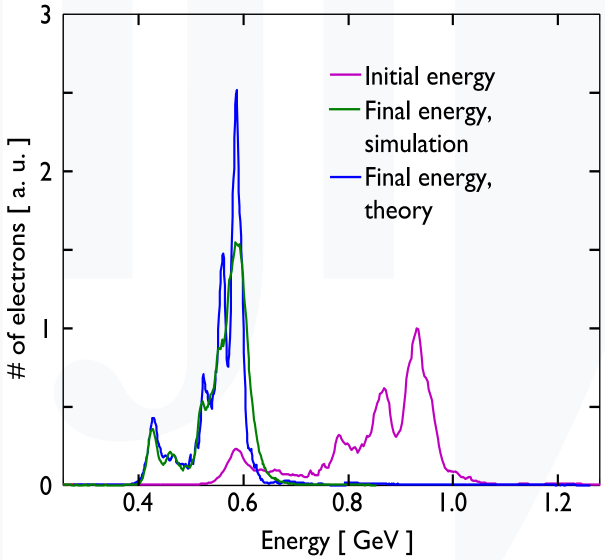
$$P = -\frac{d(\gamma mc^2)}{dt} = c\sigma_T \gamma^2 (1 - \beta\cos\theta)^2 U_{PH}$$



$$\gamma_f = \frac{\gamma_0}{1 + k\gamma_0}$$

$$k = 1.22 \times 10^{-26} I \left[\frac{\mathrm{W}}{\mathrm{cm}^2}\right] \tau_{\mathrm{fwhm}}[\mathrm{fs}]$$

Electron spectrum gets narrower



$$\frac{\delta\gamma_f}{\gamma_f} = \frac{\delta\gamma_0}{\gamma_0}\frac{1}{1 + k\gamma_0}$$

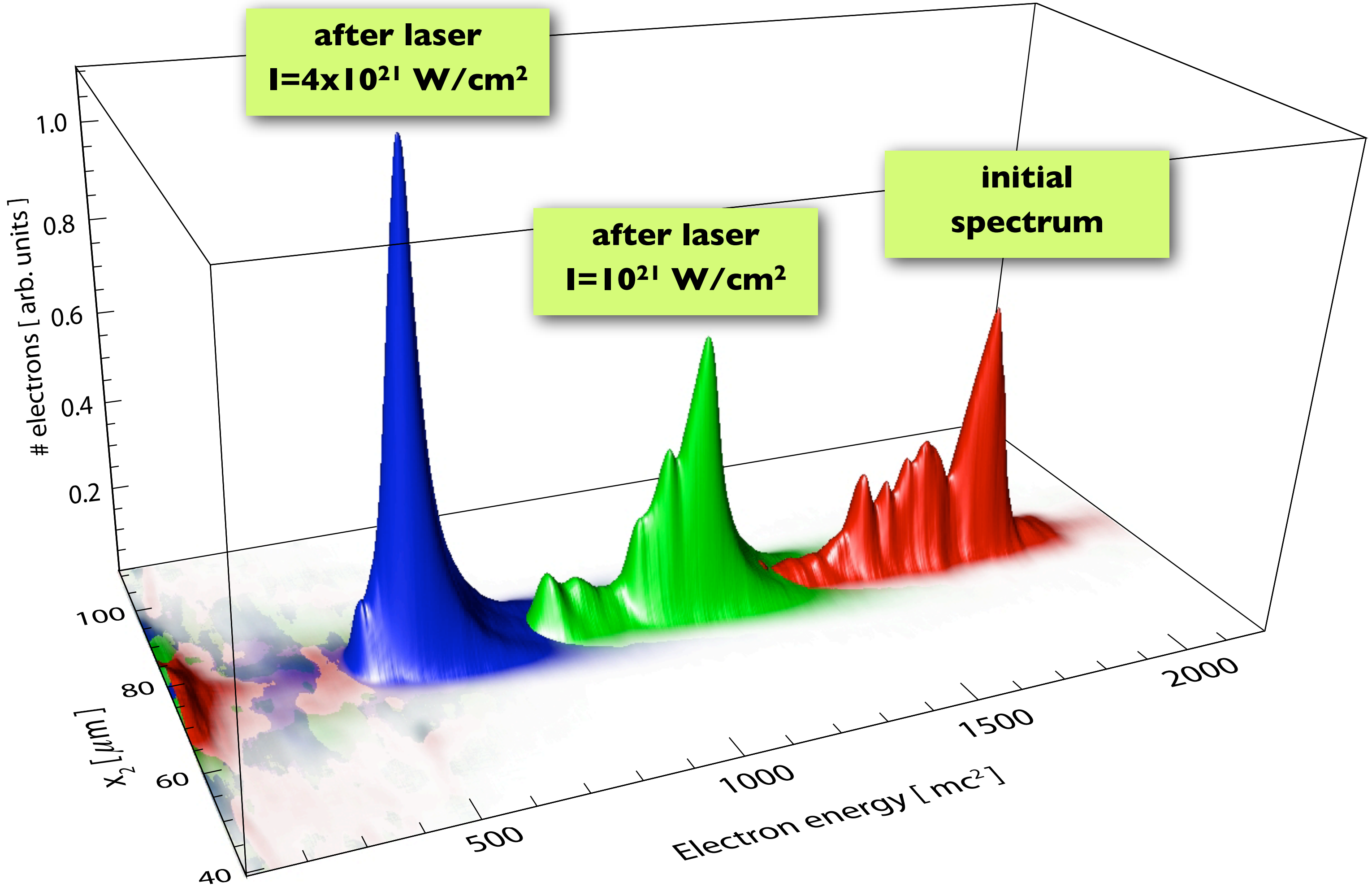
(0.9 ± 0.1) GeV

$\Downarrow$

(0.55 ± 0.05) GeV

Dramatic energy change

Observable even if the electron beam is not monoenergetic!



JRad: advanced diagnostic for radiation

J. Martins *et al*

Algorithm

- Massively parallel and optimal efficiency
- Space and time resolved spectra and total power
- Excellent agreement with theory and experiments*

Power

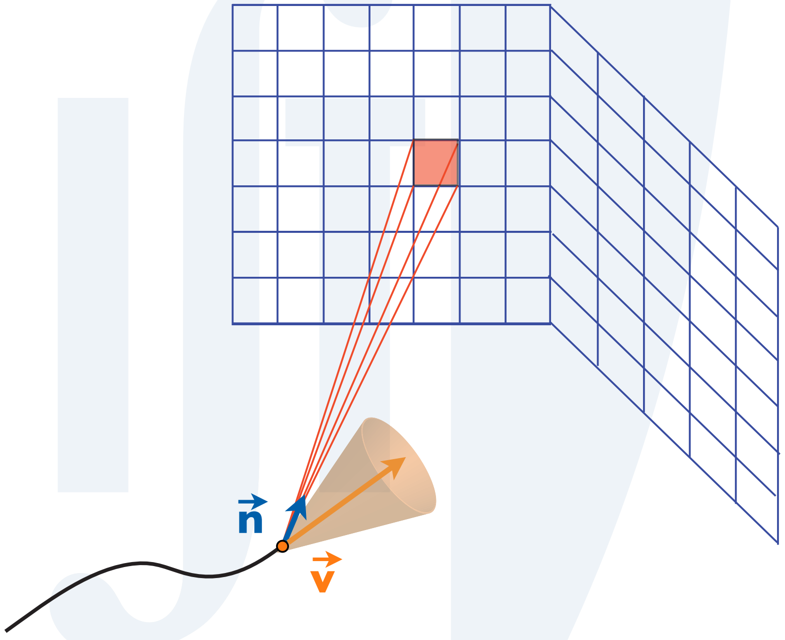
$$\frac{dP}{dS} = \frac{e^2}{4\pi c}\frac{|\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]|^2}{(1-\vec{\beta}.\vec{n})^5 R(t')^2}$$

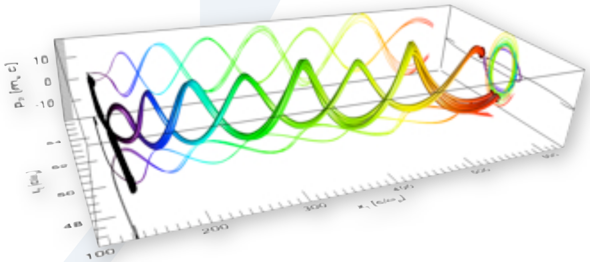
Jackson, J.D., Classical Electrodynamics

Spectrum

$$\frac{d^2 I}{d\omega dS} = \frac{e^2}{4\pi c}\left|\int_{-\infty}^{-\infty}\frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{n}\cdot\vec{\beta})^2 R(t')^2}e^{i\omega(t'+R(t')/c)}dt\right|^2$$

Jackson, J.D., Classical Electrodynamics





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*J. L. Martins et al Proc. of SPIE **7359**, 73590V (2009)
S.Kneip, C. Mcguffey, J.L.Martins et al, Nat. Phys. **6** 980-983 (2010)

QED model for radiation reaction

T. Grismayer *et al* (in collaboration with M. Marklund)

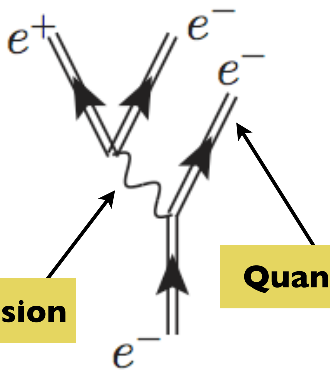
Simulating QED regime

High fields and relativistic particles require to implement **radiation reaction**

Self-consistent electron-photon dynamics → **QED approach**

On the path of the **Trident pair process**: non-linear Compton + stimulated pair production

Trident process



Photon emission

Quantum recoil

Radiation Reaction

Different types of Radiation reaction models

$$\frac{d\vec{p}}{dt} = \vec{F}_L + \begin{cases} \vec{F}_{rad} & \text{Continuous damping rate*} \\ \dfrac{d^2N}{dt\,d\chi} & \text{QED probabilistic approach**} \end{cases}$$

Implementation in PIC codes

- Continuous damping rate: particle pusher with F_{rad}
- QED probabilistic approach: particle pusher + Monte Carlo module
  - every Δt : probability of photon emission
  - Select a photon in QED synchrotron spectrum
  - Update particle momentum due to quantum recoil
- The QED approach can be generalized to any external EM fields under the conditions:
  - quasi-static fields $t_{carac}(\vec{E},\vec{B}) \gg t_{coh} \implies \gamma \gg 1$
  - weak fields $\eta^2 \gg \mathrm{Max}(f,g) \quad (f,g) \ll 1 \quad \eta = \gamma B/B_{crit}$

* Landau & Lifshitz (Theory of Fields)
** A.I Nikishov & V.I Ritus JETP (1967)

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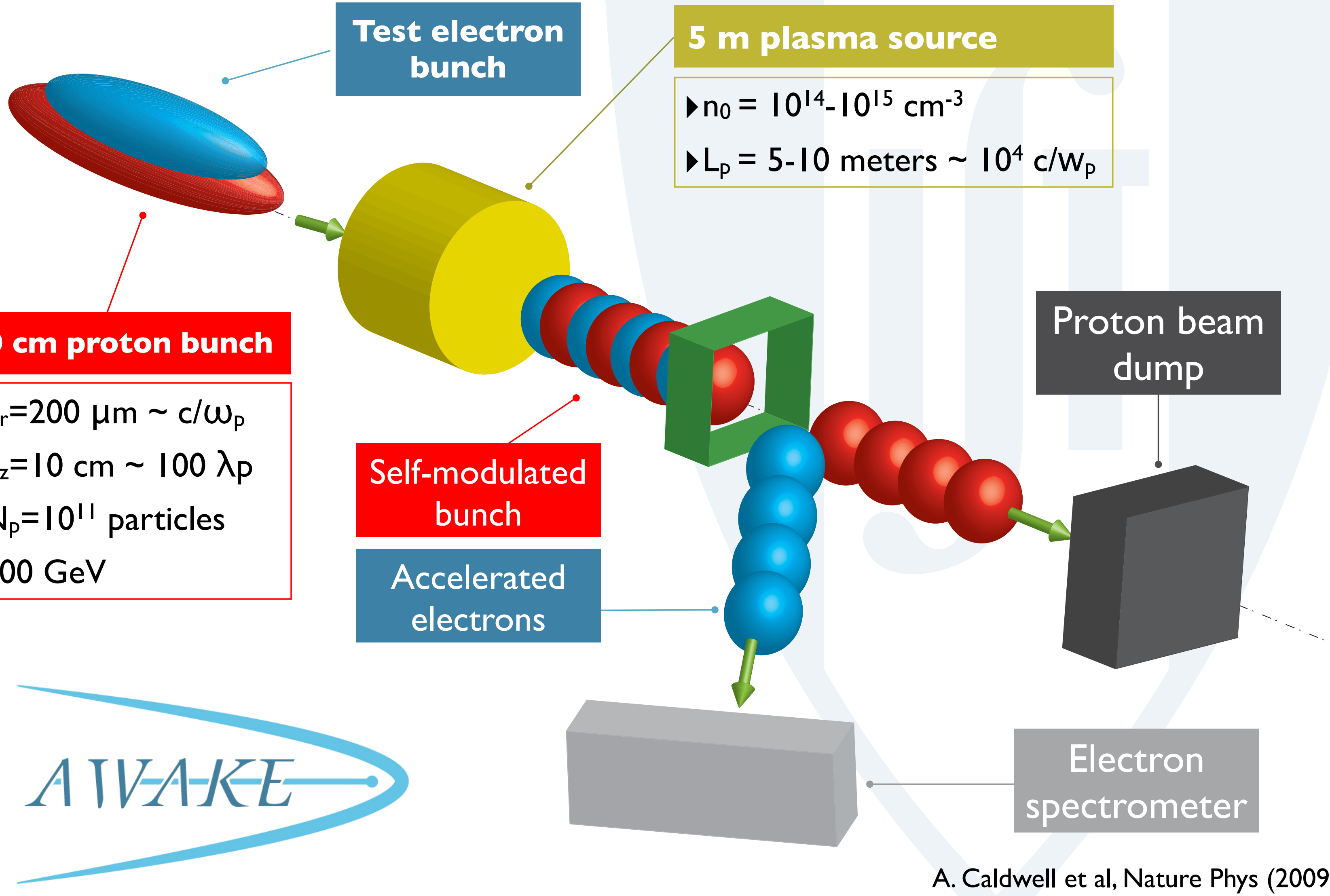
Self-modulated proton driven wakefield accelerator



Test electron bunch

5 m plasma source

- n_0 = 10^{14}-10^{15} cm^{-3}
- L_p = 5-10 meters ~ 10^4 c/w_p

10 cm proton bunch

- s_r=200 μm ~ c/ω_p
- s_z=10 cm ~ 100 λp
- N_p=10^{11} particles
- 500 GeV

Self-modulated bunch

Accelerated electrons

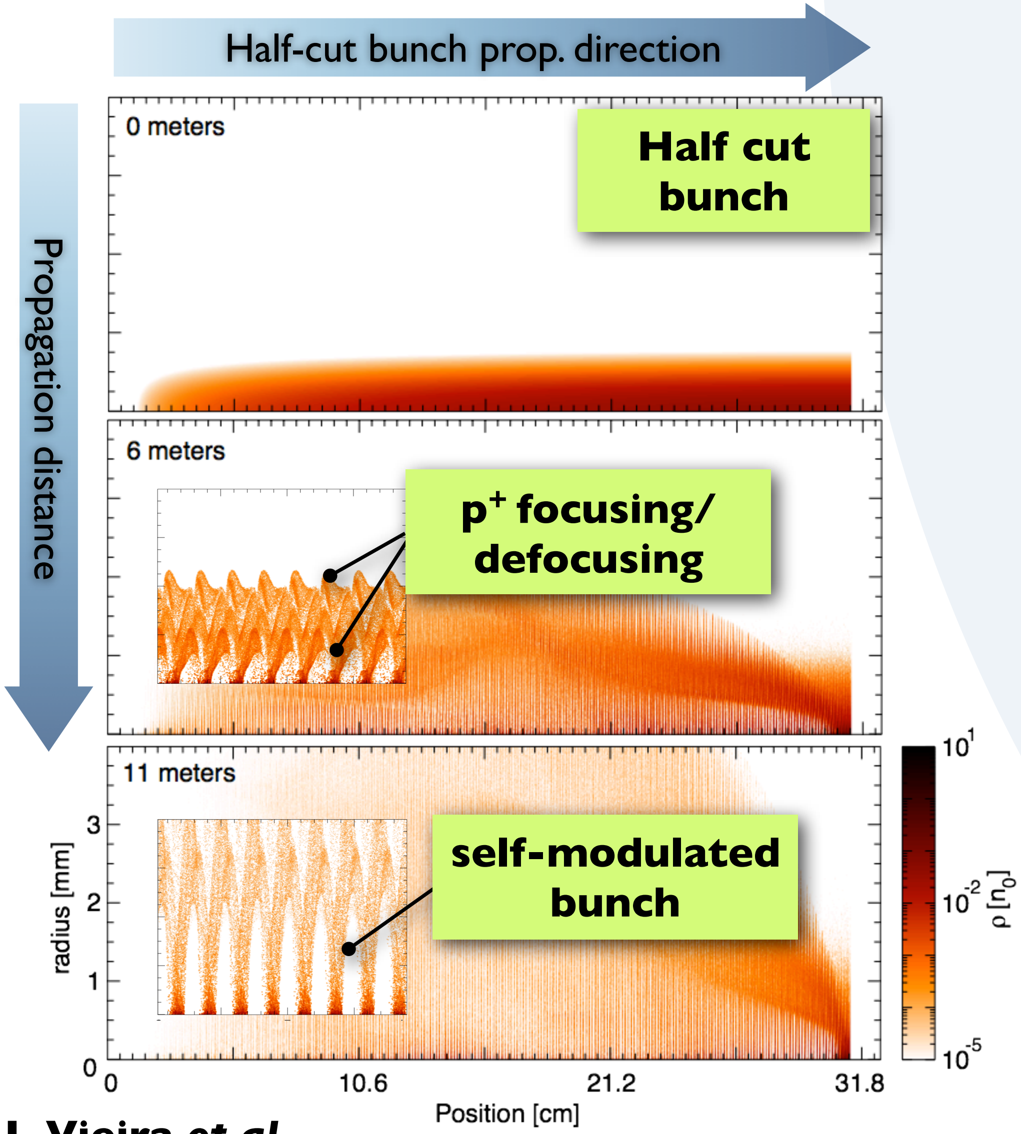
Proton beam dump

Electron spectrometer

AWAKE

A. Caldwell et al, Nature Phys (2009).

GeV e^- over 5 m long plasmas with half-cut bunches



Half-cut bunch prop. direction

Propagation distance

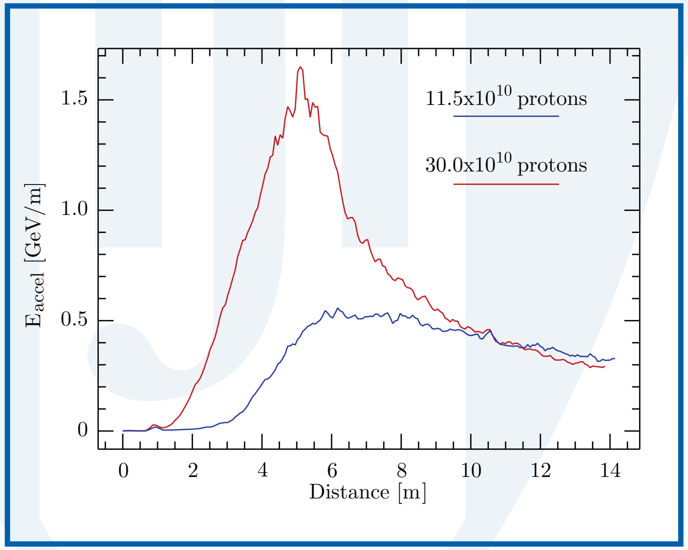
Half cut bunch

p^+ focusing/ defocusing

self-modulated bunch

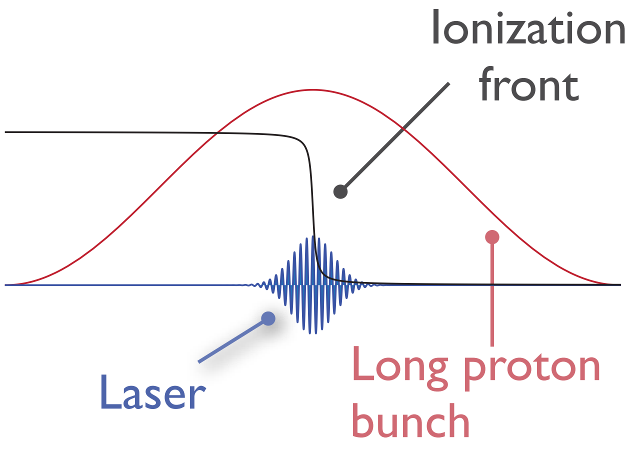
J. Vieira *et al*

Maximum accelerating gradients



Creating plasma and cut proton bunch simultaneously
Ionizing laser pulse

Laser pulse on top of proton bunch



- Laser pulse creates ionization front
- Ionization front acts as if long proton bunch is sharply cut
- Laser pulse excites wakes to directly seed the instability

D. Gordon et al, PRE, **64** 046404 (2001).

PIC simulations are demanding

- $\omega_0/\omega_p \sim 1000 - 4000$
- 1000 - 4000x smaller $\Delta x_{||}$
- 1000 - 4000x more CPUh
- **~10 million CPU hours using standard full-PIC for 5 m**

Equation for the laser envelope
Ponderomotive guiding center

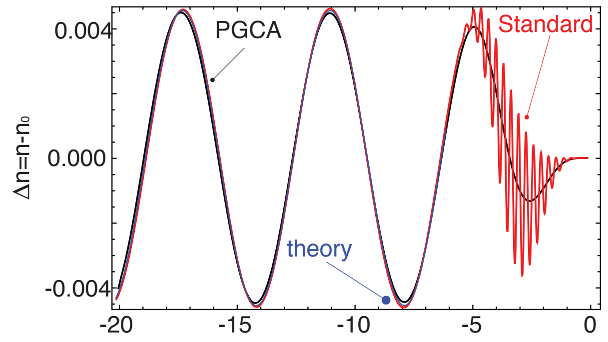
Equation for laser pulse envelope:

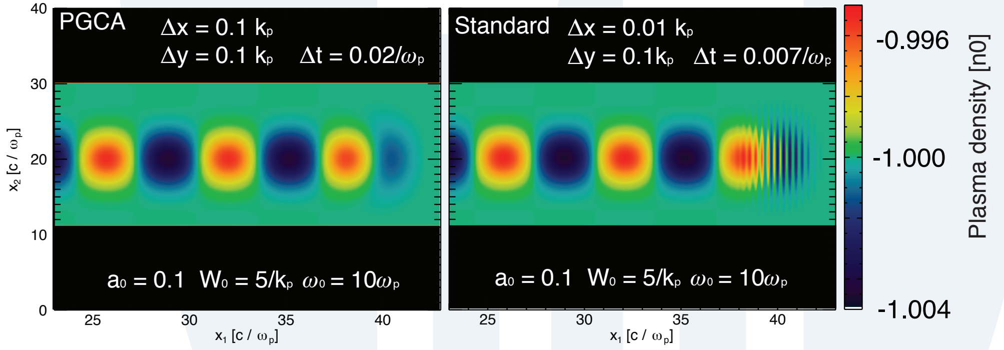
$$\underset{t=t}{\partial_\tau} a = \underset{\text{laser frequency}}{\frac{1}{2i\omega_0}}\left[\left(1+\frac{1}{i\omega_0}\underset{x=x-ct}{\frac{\partial}{\partial\xi}}\right)+\nabla_\perp^2 \underset{\text{laser envelope}}{a}\right]$$

D. Gordon, W. Mori, T. Antonsen, IEEE-TPS, **28** 1135-1143 (2000).

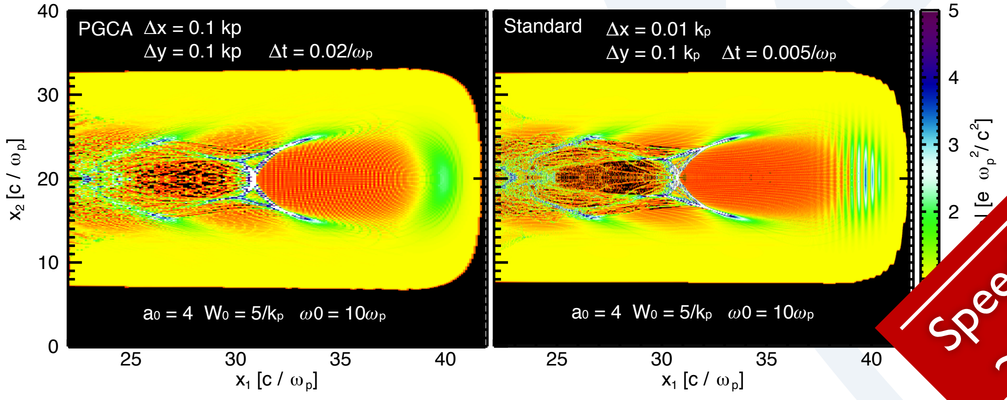
Ponderomotive guiding center agrees with full PIC

Pre-ionized plasma in linear regimes





Strongly non-linear blowout regime (ionization)



Speedup
~100x

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Summary

Multiscale modeling pushing PIC simulations to full scale modeling of wide range of scenarios

Petascale LWFA modeling

Full scale fast ignition/ion acceleration modeling

Assessing radiation reaction and QED signatures

Long propagation distances in proton driven accelerators